

Numerical study of jets produced by conical wire arrays on the Magpie pulsed power generator

M. Bocchi

m.bocchi@imperial.ac.uk

and

J. P. Chittenden

The Blackett Laboratory, Imperial College London, London, UK

and

A. Ciardi

LERMA, Université Pierre et Marie Curie, Observatoire de Paris, Meudon, France

École Normale Supérieure, Paris, France. UMR 8112 CNRS

and

F. Suzuki-Vidal

and

G. N. Hall

and

P. de Grouchy

and

S. V. Lebedev

The Blackett Laboratory, Imperial College London, London, UK

and

S. C. Bott

Center for Energy Research, University of California, San Diego, CA, USA

The final publication will be available on Springer.

ABSTRACT

The aim of this work is to model the jets produced by conical wire arrays on the MAGPIE generator, and to design and test new setups to strengthen the link between laboratory and astrophysical jets. We performed the modelling with direct three-dimensional magneto-hydro-dynamic numerical simulations using the code GORGON. We applied our code to the typical MAGPIE setup and we successfully reproduced the experiments. We found that a minimum resolution of $\sim 100 \mu m$ is required to retrieve the unstable character of the jet. We investigated the effect of changing the number of wires and found that arrays with less wires produce more unstable jets, and that this effect has magnetic origin. Finally, we studied the behaviour of the conical array together with a conical shield on top of it to reduce the presence of unwanted low density plasma flows. The resulting jet is shorter and less dense.

Subject headings: jets; laboratory astrophysics; numerical simulations

1. Introduction

Although important improvements have been achieved in the comprehension of astrophysical jets, several questions remain open, including jet formation, propagation in an external medium and survival to potentially disruptive instabilities (Bellan et al. 2009; Hardee et al. 2004). Jets produced in the laboratory are scalable to astrophysical conditions, as they are characterised by dimensionless parameters in a similar range to Young Stellar Object (YSO) jets. In particular, jets produced by conical wire arrays are especially suitable to study the interaction of the jet with an ambient medium (Lebedev et al. 2005; Ciardi et al. 2008). In this framework we produced laboratory jets on the MAGPIE pulsed power generator at Imperial College, London (Mitchell et al. 1996) using different setups: conical and radial wire arrays (Lebedev et al. 2005) and radial foils (Ciardi et al. 2009). The recent upgrade of MAGPIE and other pulsed power facilities (notably the Z machine in Sandia, USA) will allow the study of new physical regimes for jets. The work presented here aims to carefully model the experiments of jets from conical wire arrays on MAGPIE in order to understand the physics and help the design of new experimental setups and diagnostics. Direct numerical simulations are employed for the modelling, using the three-dimensional (3D) resistive magneto-hydro-dynamic (MHD) code GORGON (Chittenden et al. 2004; Ciardi et al. 2007).

1.1. Conical wire arrays

A conical wire array is composed by a set of wires placed in a conical shape (see Fig. 1) and connected to a pulsed power generator. As the electric current passes through the array, the wires are heated and transformed into plasma. The current also produces a global toroidal magnetic field which accelerates the ablated plasma in a direction perpendicular to the wires. The plasma streams are directed towards the array axis where a conical shock is formed. While the component of the

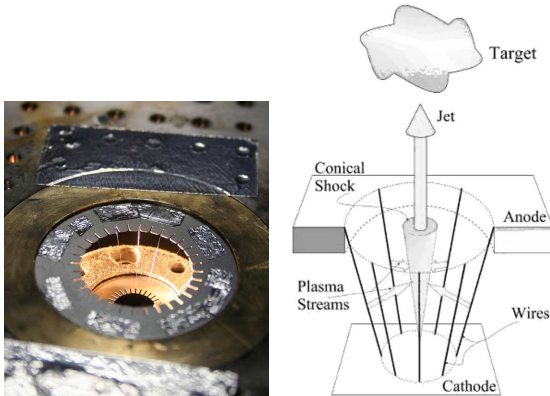


Fig. 1.— *Left Panel:* Picture of the experimental setup. *Right Panel:* Scheme of a typical conical array setup

velocity perpendicular to the shock surface is reduced by the large shock compression factor ($\sim 20 - 40$), the parallel component of the velocity remains continuous across the shock. In addition, since the conical shock has a small opening angle (with respect to the conical array angle), the post-shock flow velocity is approximately vertical, and results in a collimated jet that propagates axially.

1.2. Plan

In the next section (Sec. 2) we will briefly introduce the model and the numerical setup. We will present the results of the numerical simulations in section 3. To start, we will compare the simulations of a standard case with new data from MAGPIE experiments. In addition, we will present our results on a possible way to improve jet experiments using a conical shield above the conical array. In the last section (Sec. 4) we will draw the conclusions.

2. Model and numerical setup

2.1. Numerical code

To carry out our simulations we used the numerical code GORGON (Chittenden et al. 2004; Ciardi et al. 2007), a Van Leer type 3D numerical code designed to integrate the MHD system of equations in a single fluid approximation. The energy equations of ions and electrons are solved separately. Ohmic heating and optically thin radiation losses are also considered. Electromagnetic fields are followed by diffusing and advecting the vector potential \mathbf{A} . Zones under a cut-off density ($\rho_{vac} = 10^{-4} \text{ Kg/m}^3$) are considered a computational "vacuum", where only the wave equation for \mathbf{A} is solved.

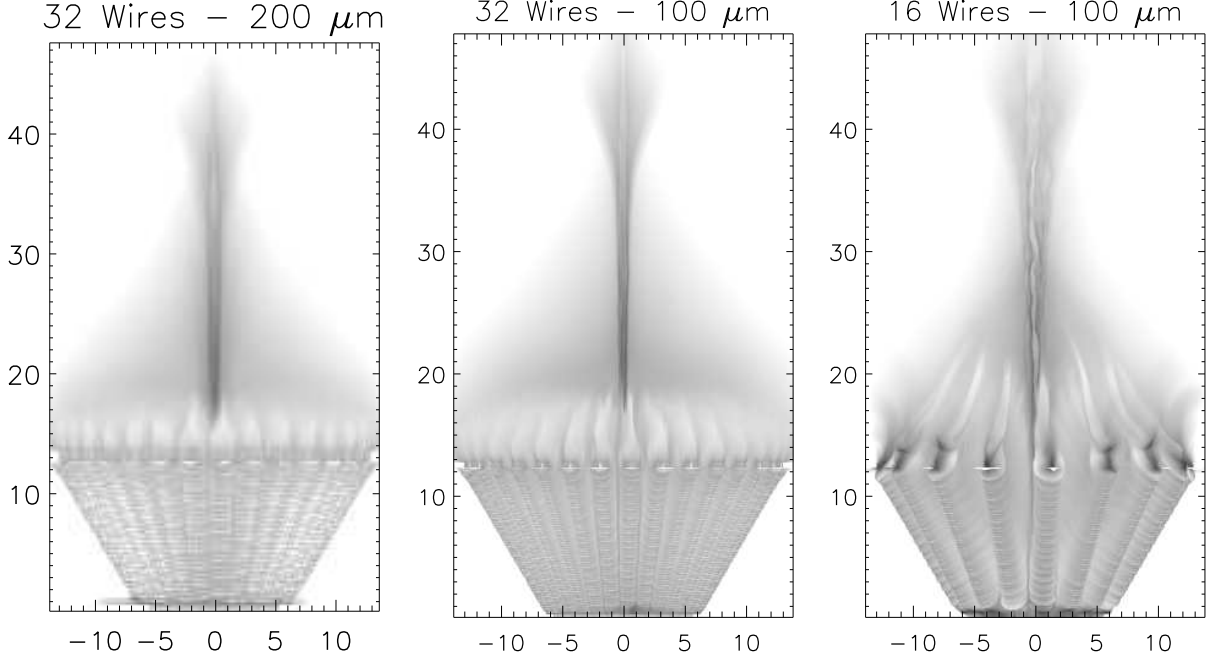


Fig. 2.— Emission maps of three different simulations at 350 ns. Darker shades correspond to higher emission. The axis are in mm units. Only part of the computational box is shown in order to highlight the jet and structures *Left Panel*: 32 wires, 200 μm resolution. *Central Panel*: 32 wires, 100 μm resolution. *Right Panel*: 16 wires, 100 μm resolution

2.2. Initial setup and numerical methods

The numerical setup has been chosen in order to mimic the recent experiments carried out on the MAGPIE facility in London. The numerical simulations employed a simplified initial setup consisting of two electrode plates connected by a variable number of equally spaced wires, as seen in Fig. 1. In the reference case studied in this paper, the cathode diameter is $d_c = 12\text{ mm}$, the anode diameter is $d_a = 21\text{ mm}$, and the array length (the distance between cathode and anode) is $l = 12\text{ mm}$. These values correspond to an inclination angle of 30.26 degrees. Either 16 or 32 wires were simulated. We modelled the electric current provided by the MAGPIE generator with the following expression:

$$I(t) = I_0 \cdot \sin^2(\pi t / 2\tau), \quad (1)$$

where $I_0 = 1.4 \cdot 10^6$ is the peak current in Ampere and $\tau = 250 \cdot 10^{-9}$ is the peak time in seconds. Computationally, this current is translated into appropriate conditions for the magnetic field at the boundaries of the computational domain.

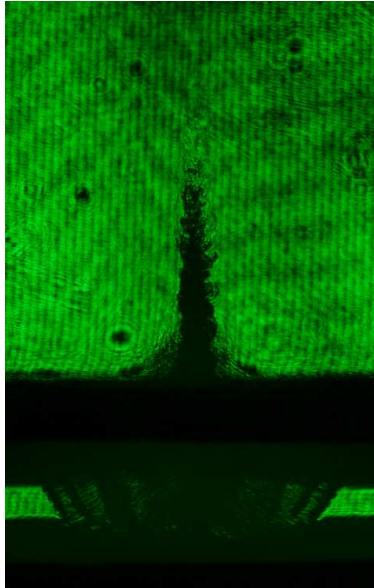


Fig. 3.— Laser shadowgram of the shot s0301_10 taken at 355 *ns*. Array of 16 tungsten wires of 18 μm diameter

3. Results

3.1. Reference Case

We investigated numerically the behaviour of a conical wire array of 16 and 32 wires inclined by 30.26 degrees with respect to the axis. The resolution of the simulations was varied between 100 and 200 μm . The self emission maps in Fig. 2 show evident differences between the various cases.

First, the jet in the high resolution simulations is more turbulent and seems unstable. Indeed, while the jet in the low resolution simulations is perfectly smooth, the high resolution counterpart presents non axisymmetric features. This is particularly evident for the 16 wires case. The unstable character of the jet is observed in the experiments, as seen in the laser shadowgram in Fig 3. In Fig. 4 we plot the electron density per unit area (n_{el}) and plasma velocity along the array axis, and draw a comparison of the various cases. The n_{el} is systematically lower and smoother in the low resolution simulation, but the shape of the curve is the same. Velocity and temperature (not shown) are similar in both high and low resolution simulations. In contrast, the current density along the jet axis is compatible only in the lower part of the jet up to $z \sim 20$ *mm*, but is sensibly higher in both 100 μm resolution simulations above this height.

The jet diameter has been measured in the experiments to be 1 - 2 *mm*. At the same time, numerical codes typically require 3 - 5 grid cells to resolve steep gradients, e.g. as the radial density gradients present at the surface of the jet. Therefore, a resolution of ~ 100 μm , or finer, is needed

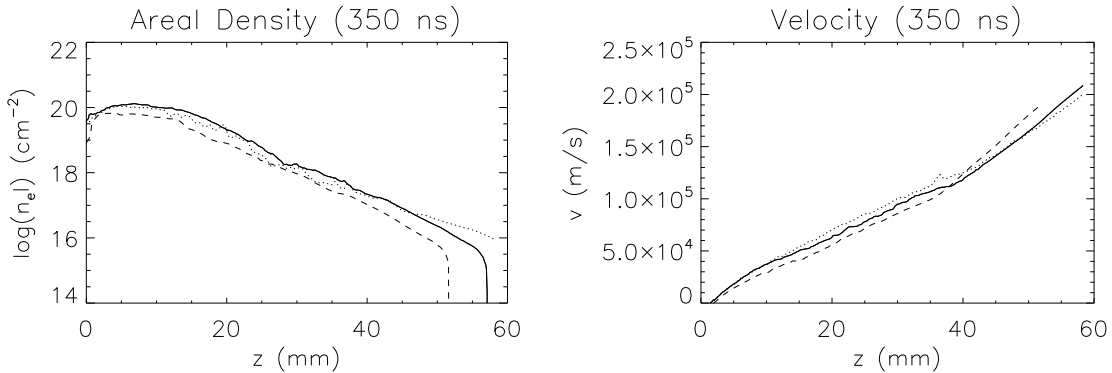


Fig. 4.— Cuts along the array axis of the areal electron number density ($n_e l$) (*Left Panel*), and of the axial component of the velocity (*Right Panel*). Data taken from various simulations at 350 ns. *Solid Line*: 32 wires, 100 μm resolution. *Dashed Line*: 32 wires, 200 μm resolution. *Dotted Line*: 16 wires, 100 μm resolution

to properly reproduce the jet profile. However, the general trend of the physical variables along the jet axis is roughly preserved in the low resolution runs.

Second, the jet produced by the 16 wires array appears to be much more unstable than the one in the 32 wires array. In addition, in the 16 wires simulation, the plasma streams at the height of the anode plate are bended inwards. The mass distribution around the jet is clearly less smooth for lower number of wires, resulting in larger perturbations on the beam. Moreover, a careful examination of the magnetic field structure reveals that, in the case of 16 wires, the magnetic field can easily penetrate the inter-wire gap and dominate the dynamics in the volume around the jet. Moreover, a small but not negligible vertical component of the magnetic field is observed. This picture is confirmed by the value of the plasma β in the region immediately around the jet, which is less than unity up to $z \sim 27$ mm. Conversely, in the 32 wires simulation, the plasma β is smaller than unity only up to $z \sim 15$ mm, just few millimetres above the anode. This suggests that the difference observed in the emission maps is partially due to magnetic effects.

3.2. Conical Shield

Conical wire arrays can be used to study the interaction of the jet with a target. Properly chosen targets allow for experiments relevant to the astrophysical scenario of a YSO jet interacting with the interstellar medium. However, as can be argued from Fig. 2, the laboratory jet is surrounded by low density material, which can interact with the target and change the properties of it before the actual interaction. In order to reduce the importance of such low density plasma, we tested a conical shield positioned above the array. The shield is designed to be perpendicular to the wires to prevent material to flow vertically above it. The thick black lines in Fig. 6 illustrate

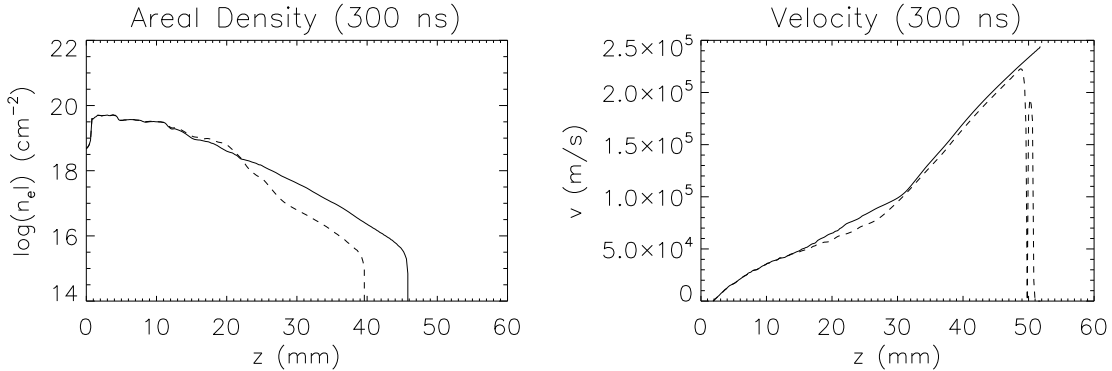


Fig. 5.— Cuts along the array axis of the areal electron number density ($n_e l$) (*Left Panel*), and of the axial component of the velocity (*Right Panel*). Data taken from the 32 wires simulation at 200 μm resolution, at 300 ns. *Solid Line*: No conical shield. *Dashed Line*: Conical shield with 8 mm aperture diameter

the position of the conical shield with respect to the wire array.

The results presented in this section refer to a 32 wires array simulation with 200 μm resolution. As explained in the previous section (Sec. 3.1), such a resolution is not sufficient to reproduce all the details of the experiment, but gives insights on the behaviour of the physical quantities, in particular of density and velocity. In Fig. 5 we plot the velocity and $n_e l$ along the jet axis at 300 ns for the same array with and without the conical shield. It is evident that the presence of the shield does not affect the velocity of the flow by a considerable amount. However, the $n_e l$ plot reveals several differences between the two cases. In the presence of a conical shield, the jet is shorter and notably less dense. The small bump in $n_e l$ at $z \sim 20 \text{ mm}$ corresponds to a higher density feature at the conical shield opening. This feature is the main source of self emitted radiation, while the jet itself emits less than in the case without conical shield (Fig. 6). The final jet is indeed free from potentially disturbing low density material around it, but the lower density and reduced length make it less useful for interaction experiments.

4. Conclusions

In this paper we presented the results of our numerical investigation on the jets produced by conical wire arrays on the pulsed power generator MAGPIE in London.

First, we found that the resolution employed for the simulations plays a crucial role to correctly reproduce the experiments. Indeed, only a resolution of $\sim 100 \mu\text{m}$ allowed us to reproduce successfully the jet unstable character observed in the experiments. Coarser resolutions proved to be insufficient to resolve the details in the jet. However, they could be used as an approximation

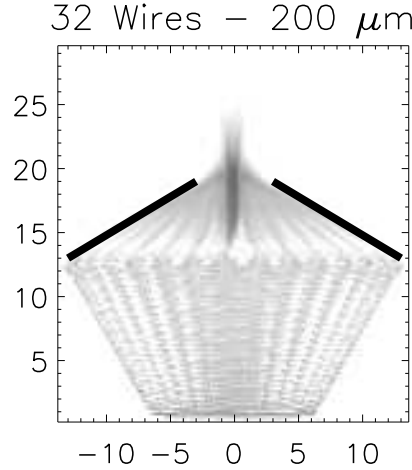


Fig. 6.— Emission map of the array simulation with conical shield at 300 ns. Darker shades correspond to higher emission. The axis are in mm units. Only part of the computational box is shown in order to highlight the jet and structures. The thick black lines represent a section of the conical shield

of the general trend of the physical variables in the jet.

Second, we investigated the effects of a different number of wires in the array. Higher wire numbers mean smoother mass distribution and smaller inter-wire gaps, therefore smaller perturbations and a much smoother distribution of the magnetic field. In the case of large inter-wire gaps however, the local magnetic field generated around each wire gives an important contribution to the global field. The resulting magnetic field is therefore much stronger in between the wires and extends far deeper into the array and nearer to the jet. This difference in mass distribution and magnetic field structure is the reason for the enhanced unstable character of the jet produced by the 16 wires array, as compared to the jet in the 32 wires array.

Lastly, we simulated the behaviour of a conical array in the presence of a conical shield. This was done to prevent the presence of low density plasma and flow above the array. Such plasma could potentially perturb the system in jet-target interaction experiments. In comparison to the arrays without conical shield, we found that the resulting jet has similar velocity but is shorter and much less dense. The overall momentum is strongly reduced, therefore this setup is not very suitable for jet-target interaction experiments.

This work is the basis for a deeper numerical investigation which will take into consideration, among others, the effects of the inclination angle on the resulting jet. Such study will be supported by, and integrated with, new sets of experiments both on MAGPIE in London and on the "Z" generator in Sandia, USA. We also plan to perform experiments of the interaction of the jet with a gas target.

Indeed, our main focus and final goal is to connect experiments and simulations with the astrophysical scenario. YSO jets form deeply into molecular clouds and pierce through them during their propagation. Several details of the interaction between the jet and the cloud are still not completely understood. The most evident signature of the interaction is the strong bow shock at the head of the jet, the structure of which is the subject of numerous studies. Along its path, the jet entrains material from the surrounding ambient medium. The morphology and dynamic of these regions are of great interest for the study of the chemical evolution and turbulent behaviour of molecular clouds. Finally, plasma instabilities can affect the jet and potentially disrupt the flow. Laboratory jets give us the opportunity to study such aspects in detail taking advantage of the accurate diagnostics available to plasma physicists, therefore they are a very useful tool to understand astrophysical jets.

This work was supported by the EPSRC Grant No. EP/G001324/1 and by the NNSA under DOE Cooperative Agreements No. DE-F03-02NA00057 and No. DE-SC-0001063. Part of the simulations presented here were run on the Jade supercomputer (GENCI-CINES, Paris-Montpellier, France), with the support of the HPC-Europa2 project funded by the European Commission - DG Research in the Seventh Framework Programme under grant agreement No. 228398.

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